

Exploring polarized vector bosons to measure the Higgs boson properties in diboson channels

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Higgs physics



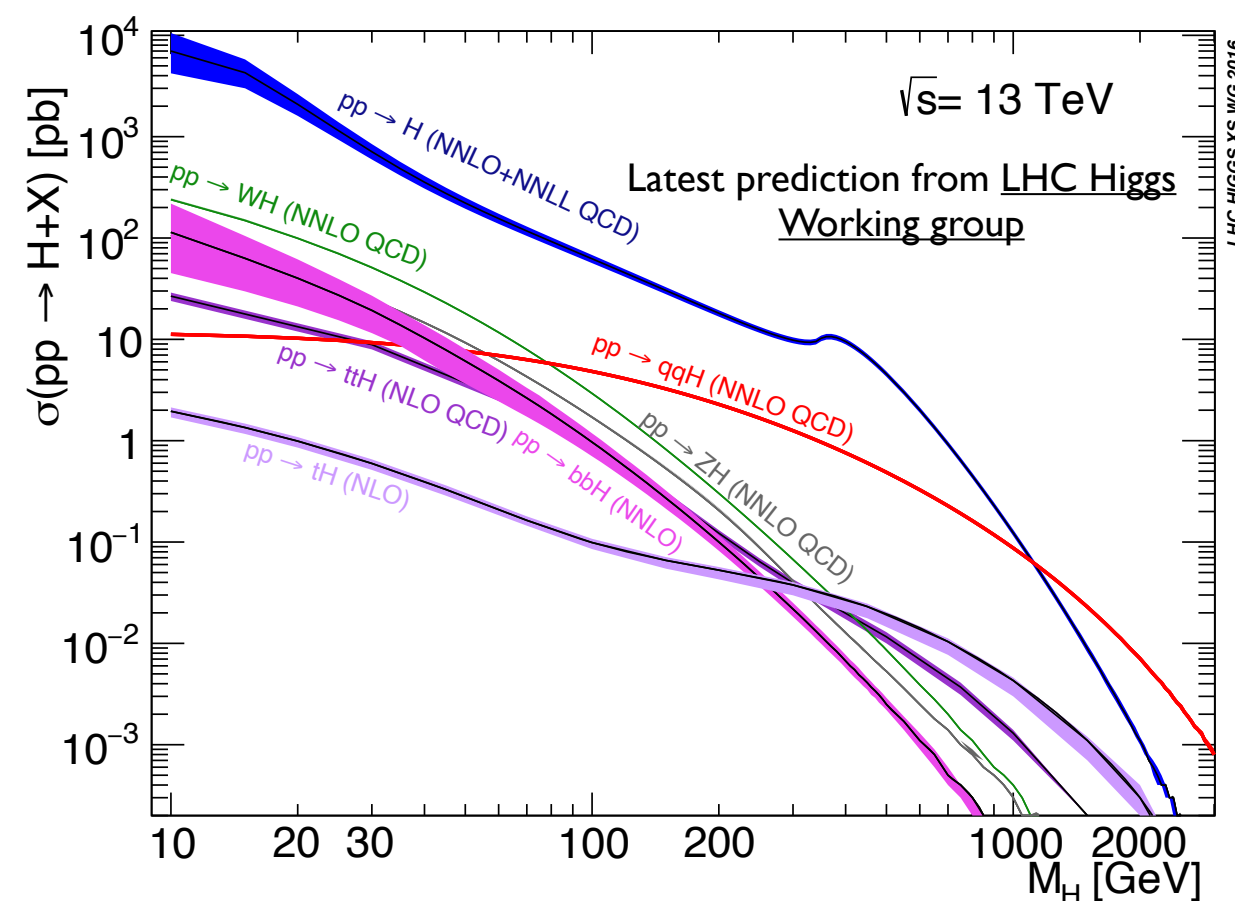
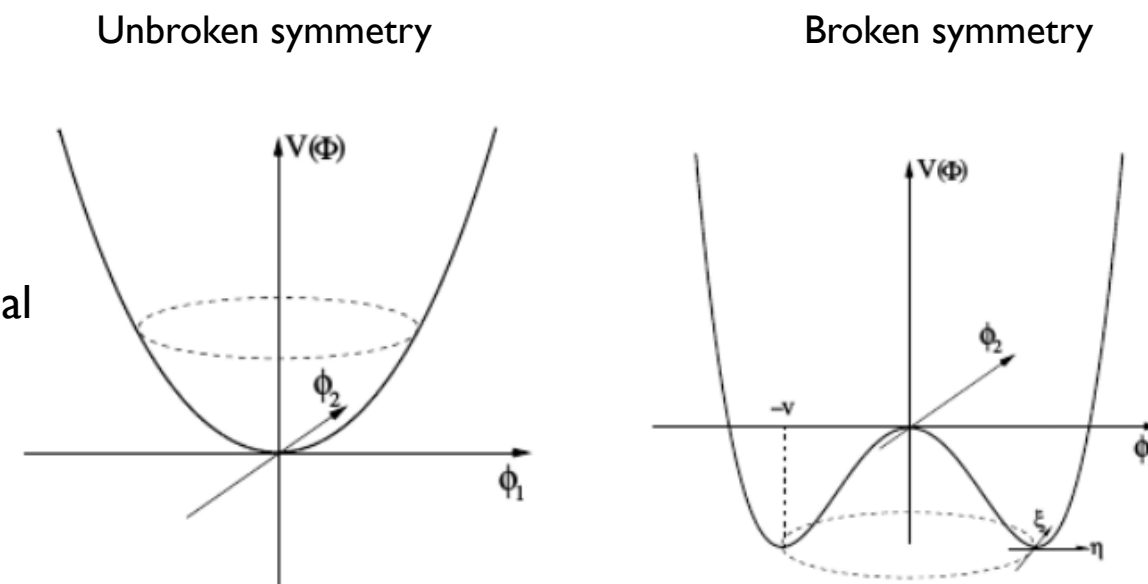
- Discovery at Run-I opened the path for properties measurements at Run-2

Power law expansion of the potential

$$V(h) = \frac{1}{4}\lambda h^4 + \lambda v h^3 + \lambda v^2 h^2$$

- Understanding the perturbative expansion of its potential ($\lambda v^2 h^2$).
- The Higgs boson (H) mass (m_H) is a fundamental parameter of the Standard Model.
- Precise measurements the Higgs interactions can indicate presence of new physics.

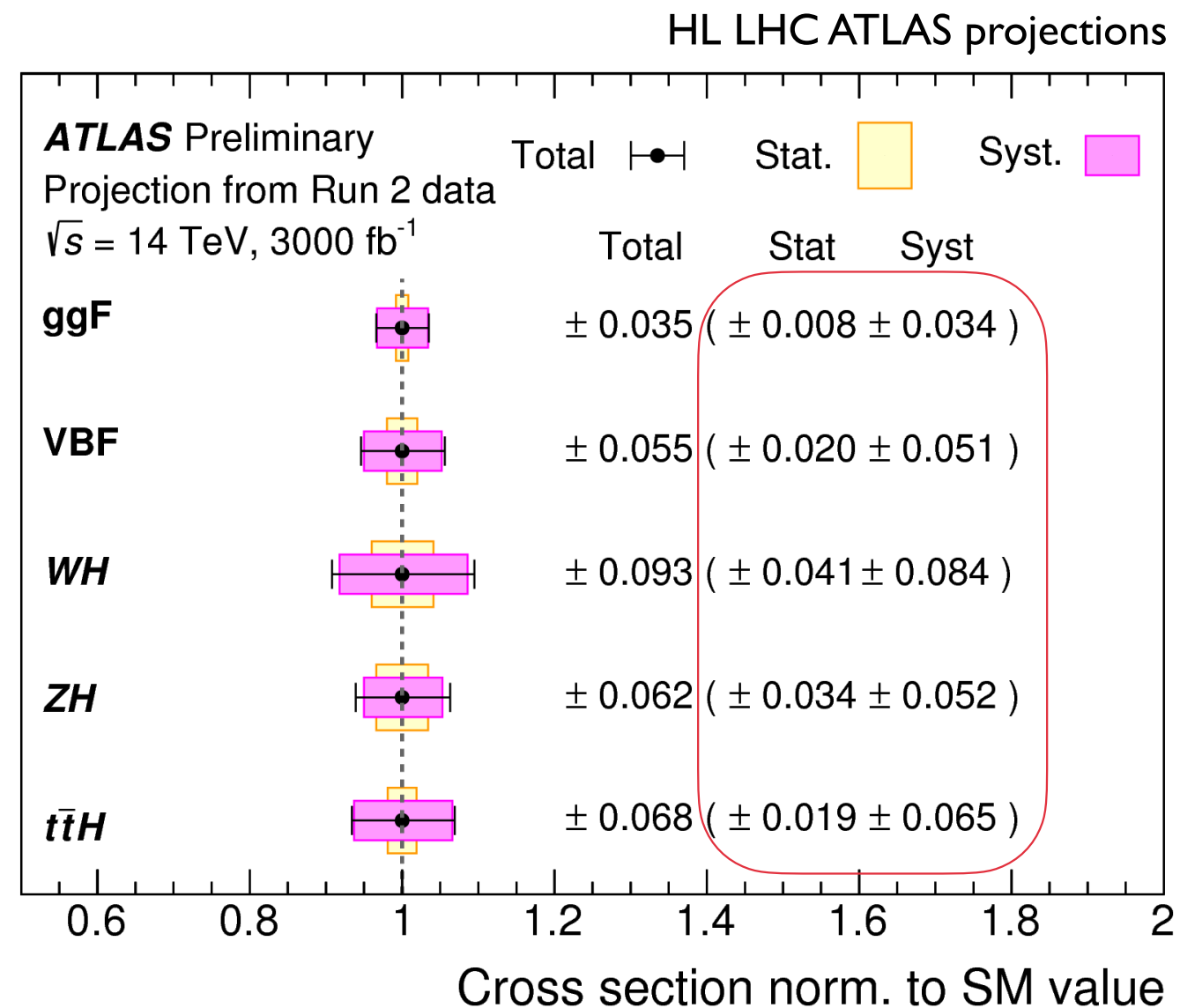
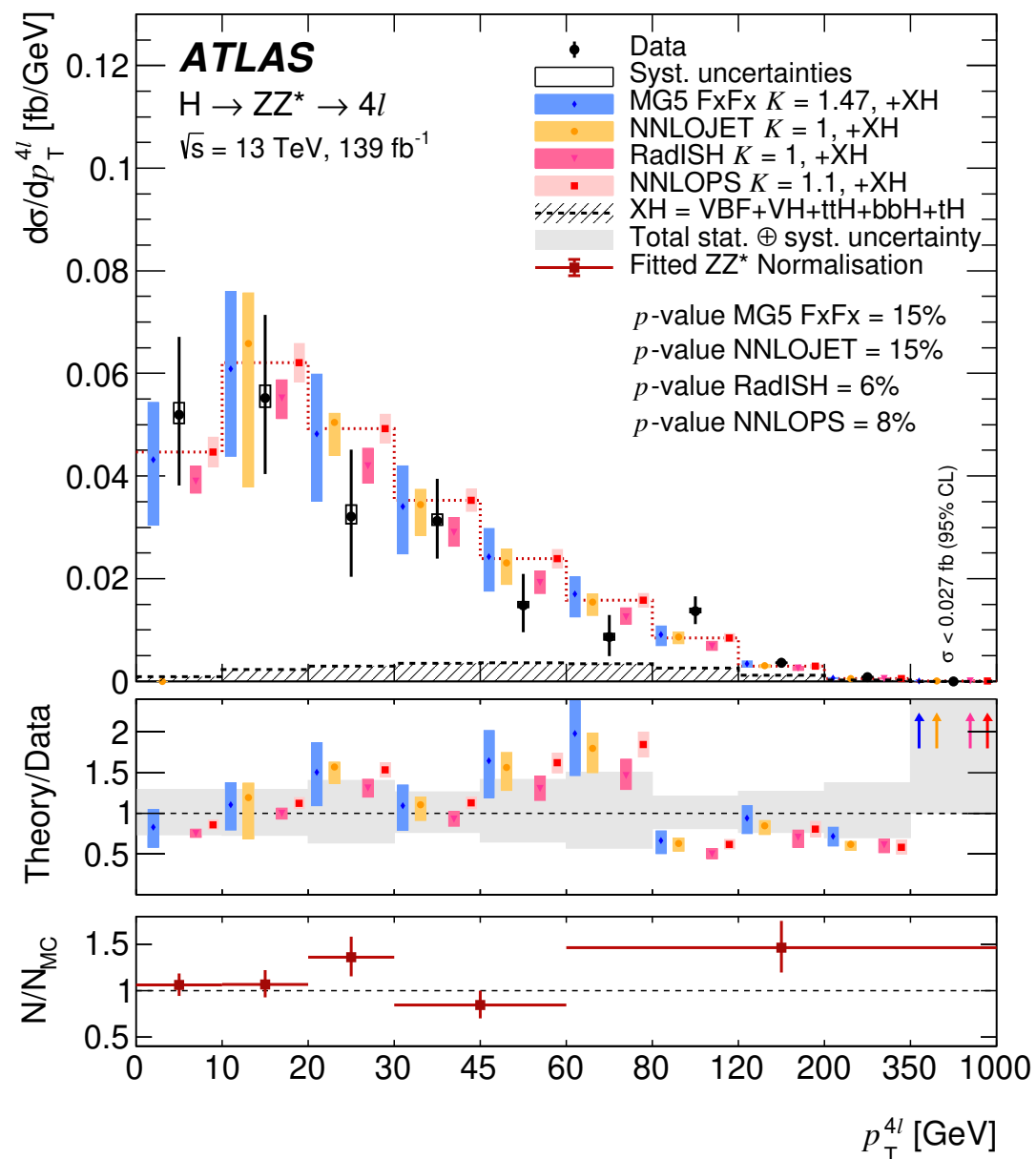
The Higgs sector is a portal to constraining the understanding of undiscovered phenomena



Prediction and uncertainties of Higgs production processes as a function of the m_H

Introduction

- Measurements of the Higgs properties on its pole.
 - Direct measurement and sensitivity to couplings ($\kappa_g \kappa_V \kappa_t$) ~ the current LHC program.
- Current reach same order of magnitude as that expected with 20 times the data.
 - New ideas needed to extend the reach in phase-space and to constrain systematics.



Off shell

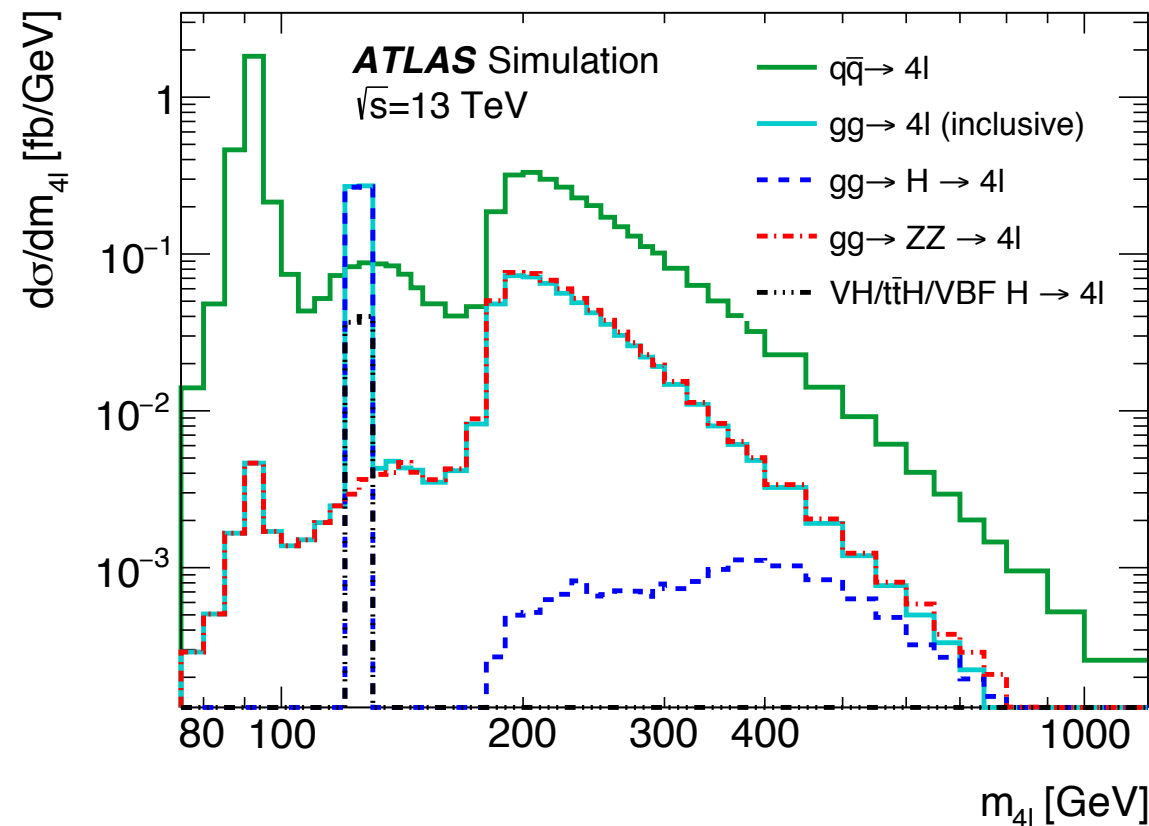
- Sensitivity from on shell production.

- ▶ Direct measurement and sensitivity to couplings (κ_g κ_V κ_t).

$$|H|^2 = \frac{1}{2} (v^2 + 2hv + h^2 + 2\phi^+ \phi^- + (\phi^0)^2)$$

- Investigate study of H couplings in off-shell production.

- ▶ Sensitivity in longitudinally polarised vector bosons production.



- Simultaneous study from same final state at different energy regimes:

- ▶ capturing energy dependence induced by new phenomena
- ▶ leverage arm on $H(HH)$ couplings from measurements at different energy regimes.

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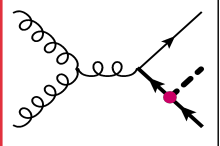
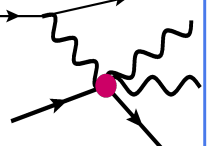
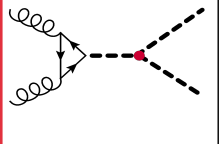
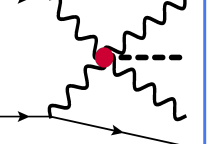
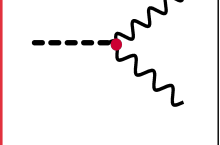
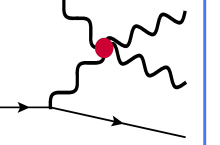
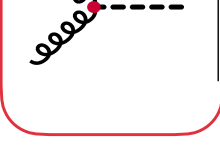
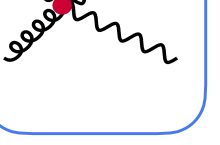
- ▶ Sensitivity in longitudinally polarised vector bosons production.

$$\kappa_g : pp \rightarrow W_L^+ W_L^-, Z_L Z_L$$

$$\kappa_t : pp \rightarrow jt + V_L V_L'$$

$$\kappa_V : pp \rightarrow jj + V_L V_L',$$

arXiv:1812.09299

		HC	HwH	Growth
κ_t	\mathcal{O}_{yt}			$\sim \frac{E^2}{\Lambda^2}$
κ_λ	\mathcal{O}_6			$\sim \frac{vE}{\Lambda^2}$
$\kappa_{Z\gamma}$ $\kappa_{\gamma\gamma}$ κ_V	\mathcal{O}_{WW} \mathcal{O}_{BB} \mathcal{O}_r			$\sim \frac{E^2}{\Lambda^2}$
κ_g	\mathcal{O}_{gg}			$\sim \frac{E^2}{\Lambda^2}$

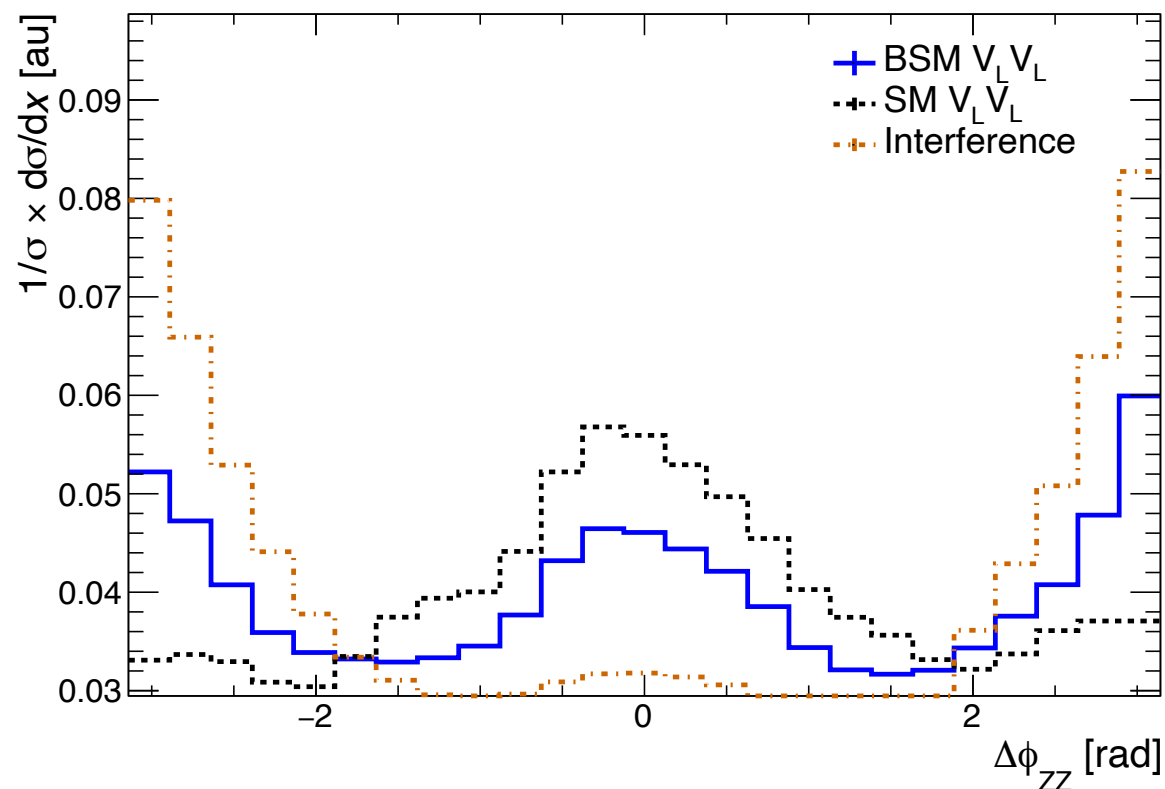
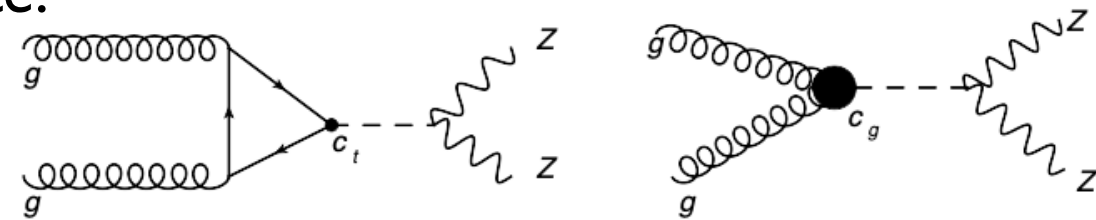
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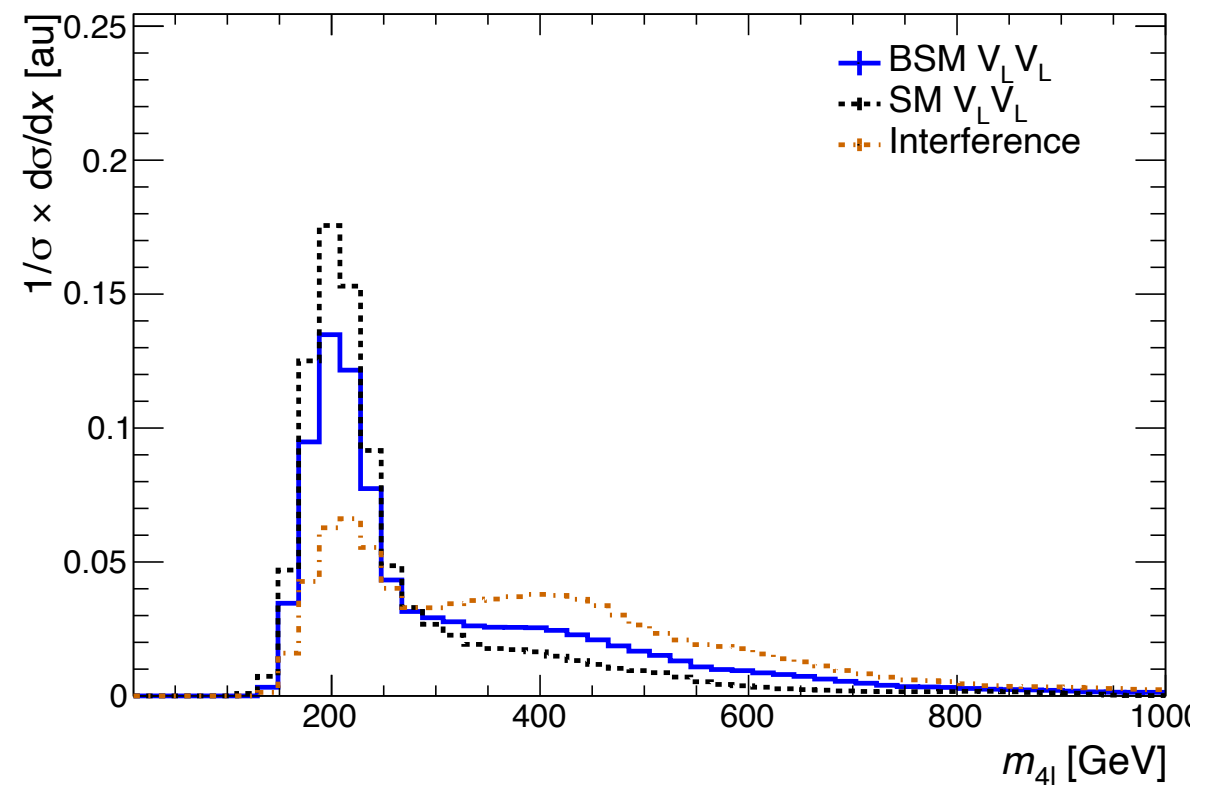
The 4ℓ final state

- Use SMEFT for probing the sensitivity to BSM couplings
 - ▶ Produced dedicated samples for signal and background and different polarisation states.
 - ▶ Currently probing c_{pg} and c_{pt}
- Focus (first) on the very pure $H \rightarrow ZZ \rightarrow 4\ell (+jj)$ final state.

- ▶ Final state selection $p_T(\ell) > 5 \text{ GeV}$ and $|\eta| < 2.7$.
- ▶ Isolate sensitivity to Higgs couplings in $gg(\rightarrow H) \rightarrow Z_L Z_L$
- ▶ Exploit differences between $qq \rightarrow ZZ$ and $gg \rightarrow Z_L Z_L$



$$C_{pg} \sim K_g$$



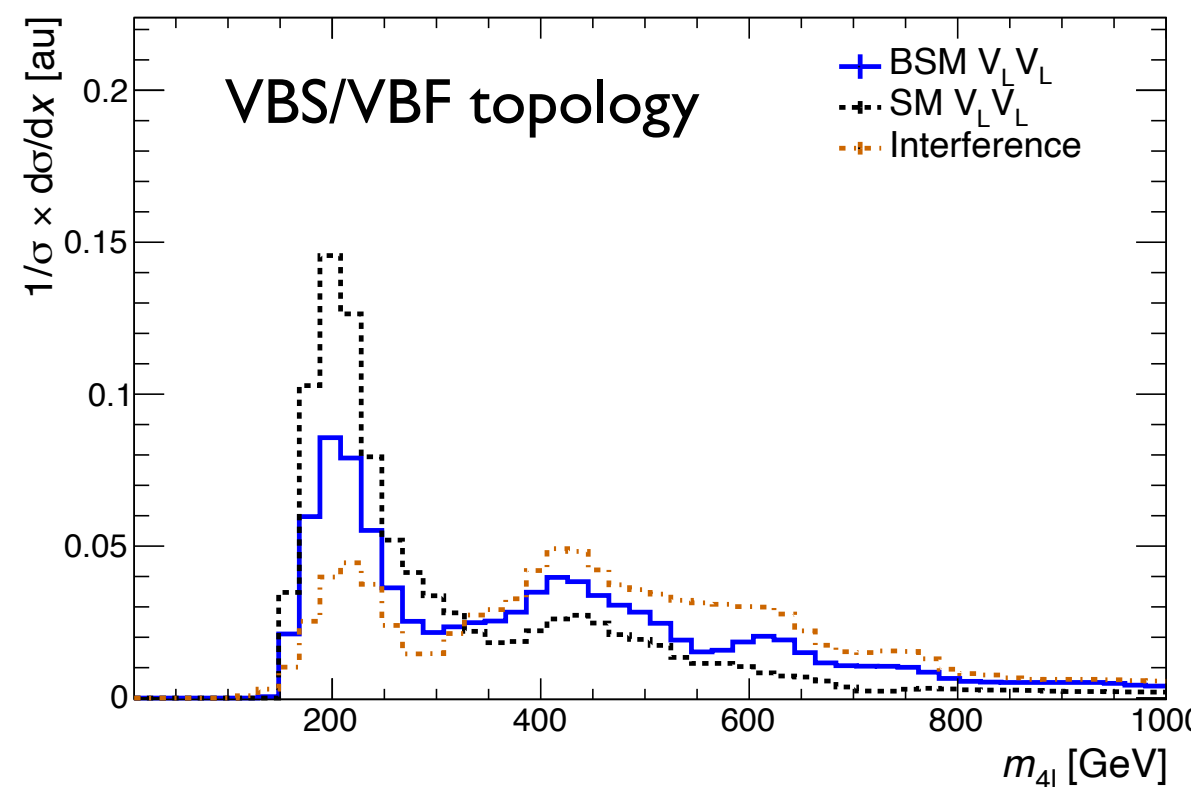
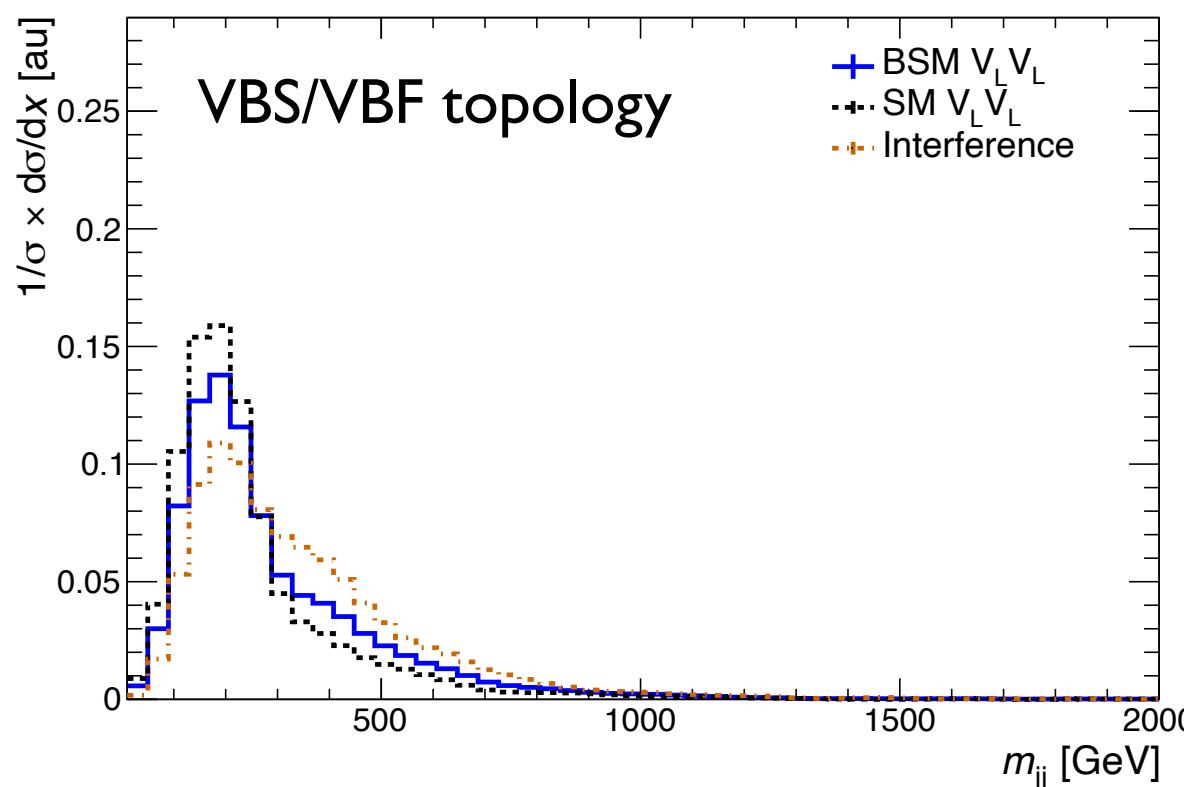
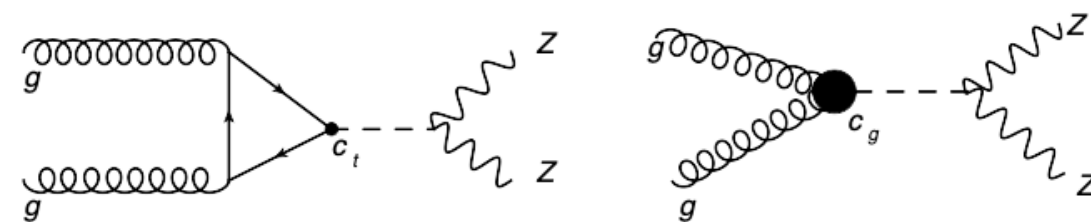
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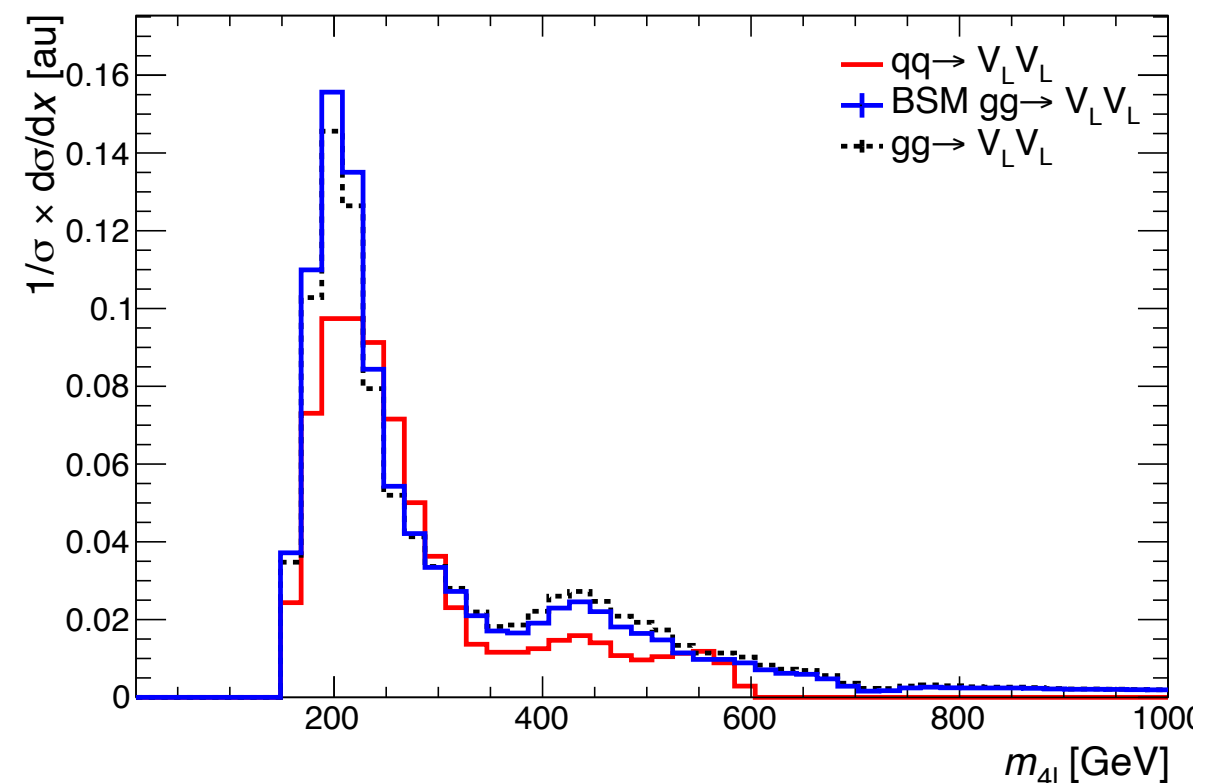
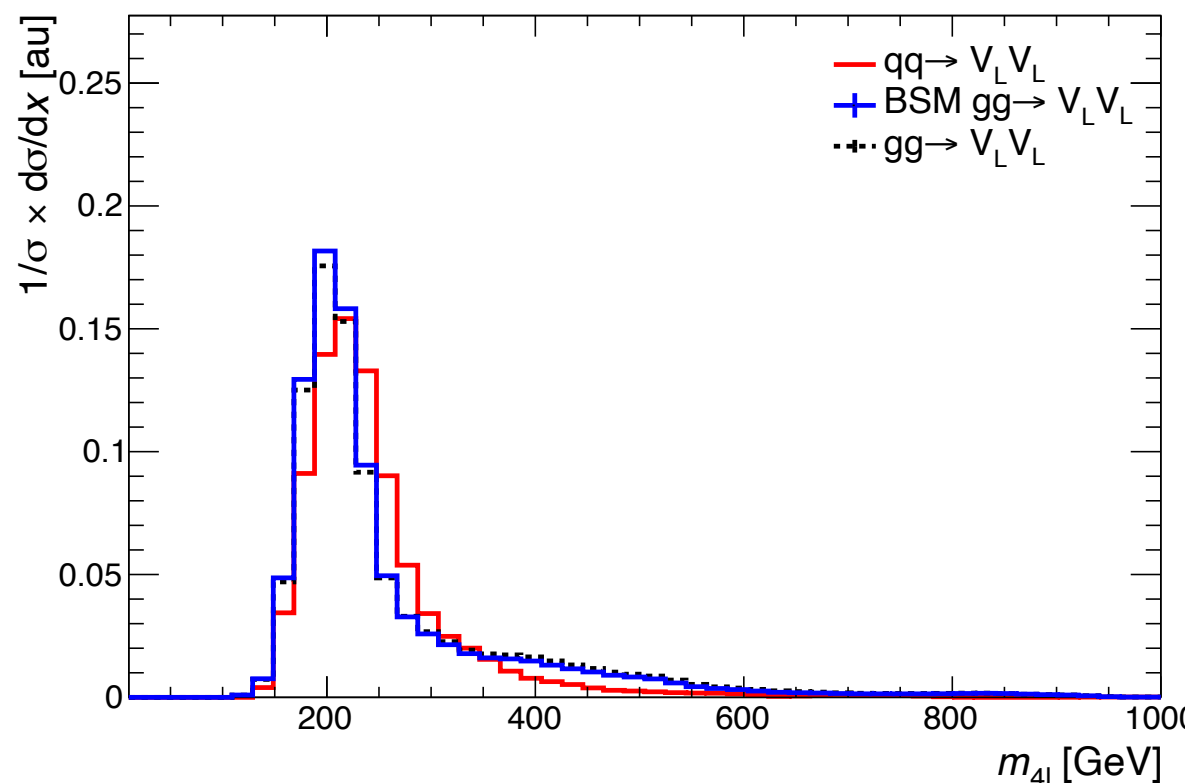
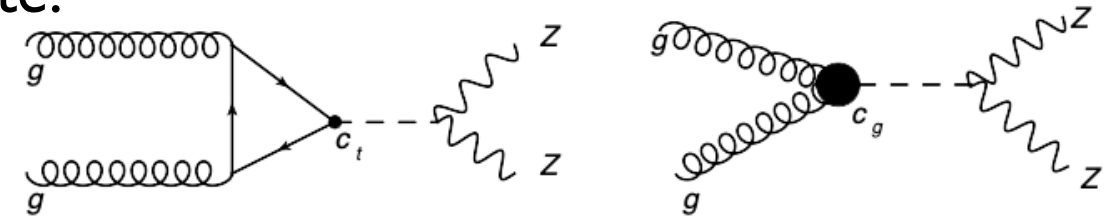


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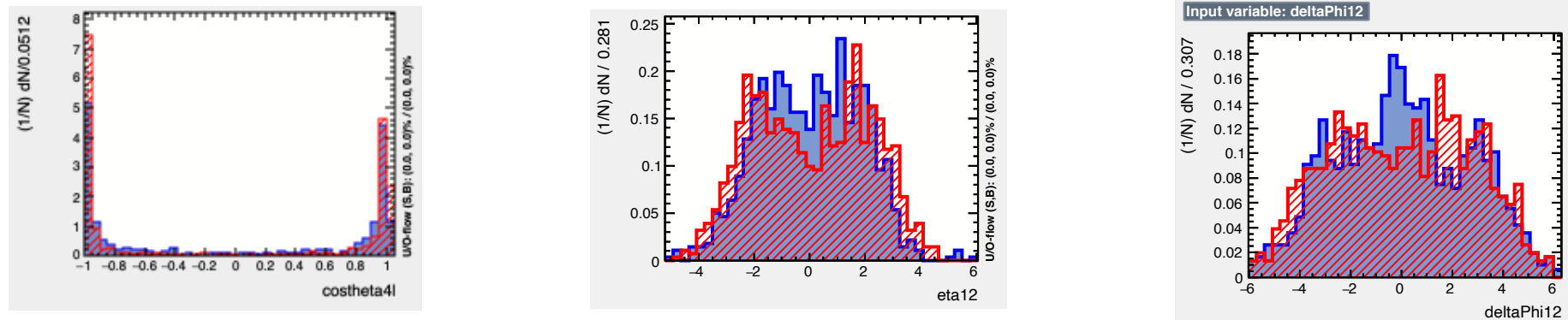
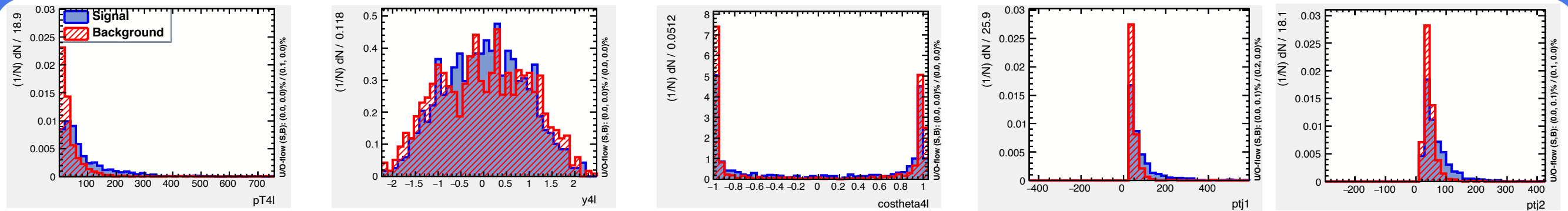


Analysis structure

- Make use angular distributions in multivariate analysis to discriminate:

(i) Between $qq \rightarrow ZZ$ and $gg \rightarrow Z_L Z_L$

(ii) Isolate polarisation states of vector bosons.

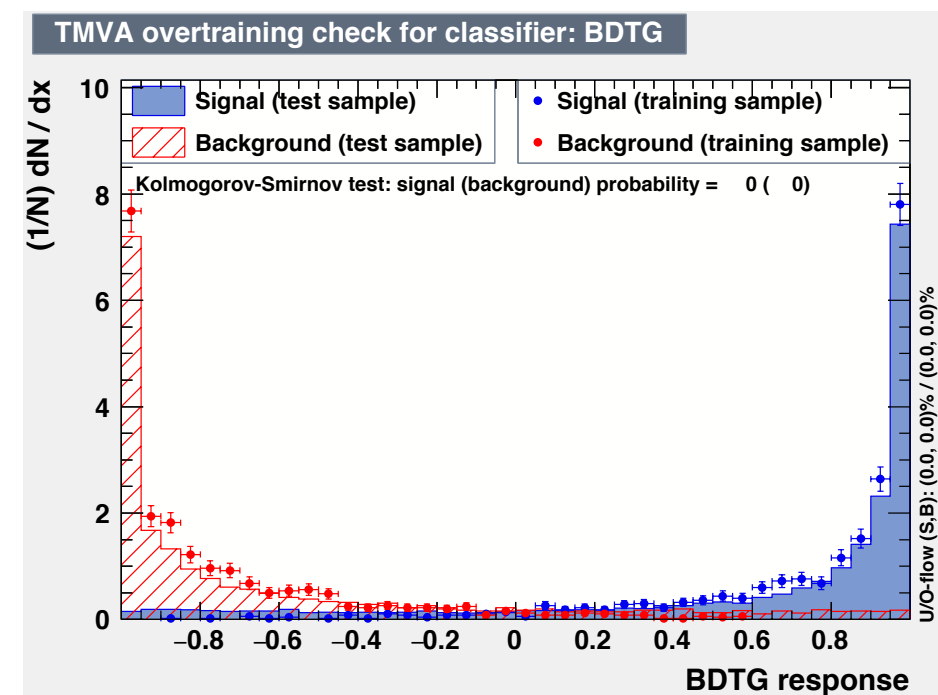
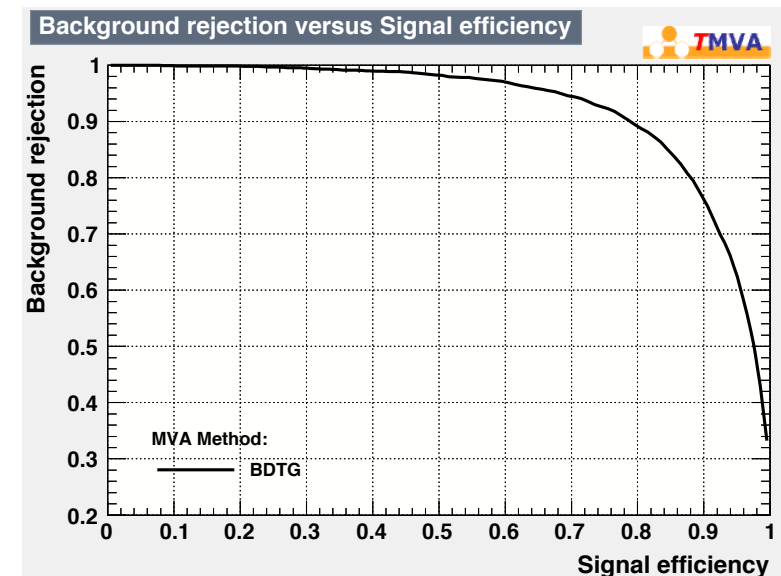
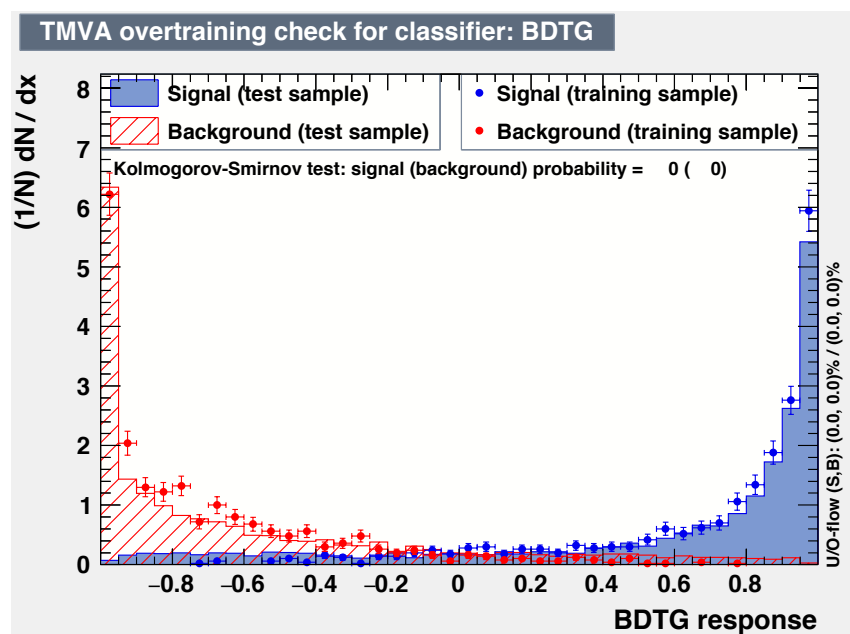
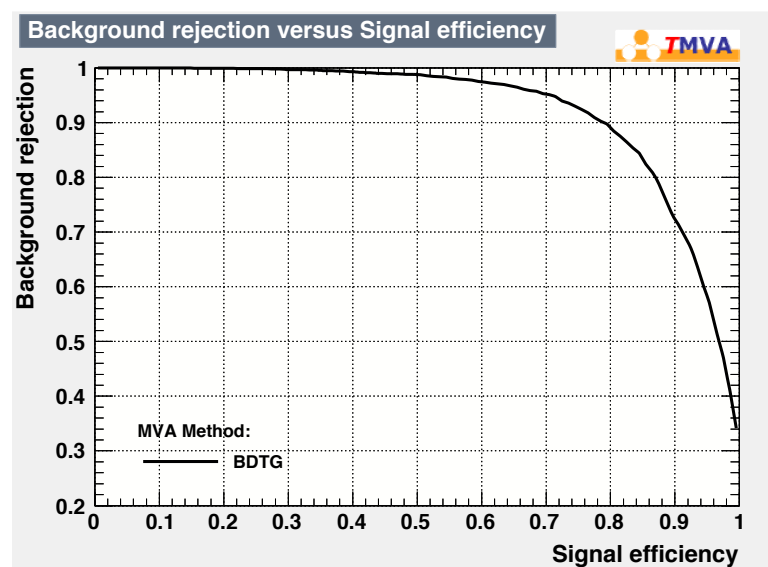


Analysis structure

- 2D analysis structure, for categorising qq -induced and gg -induced polarised vector bosons

(i) Between $qq \rightarrow ZZ$ and $gg \rightarrow Z_L Z_L$

(ii) Isolate polarisation states of vector bosons.



Conclusions & Next steps

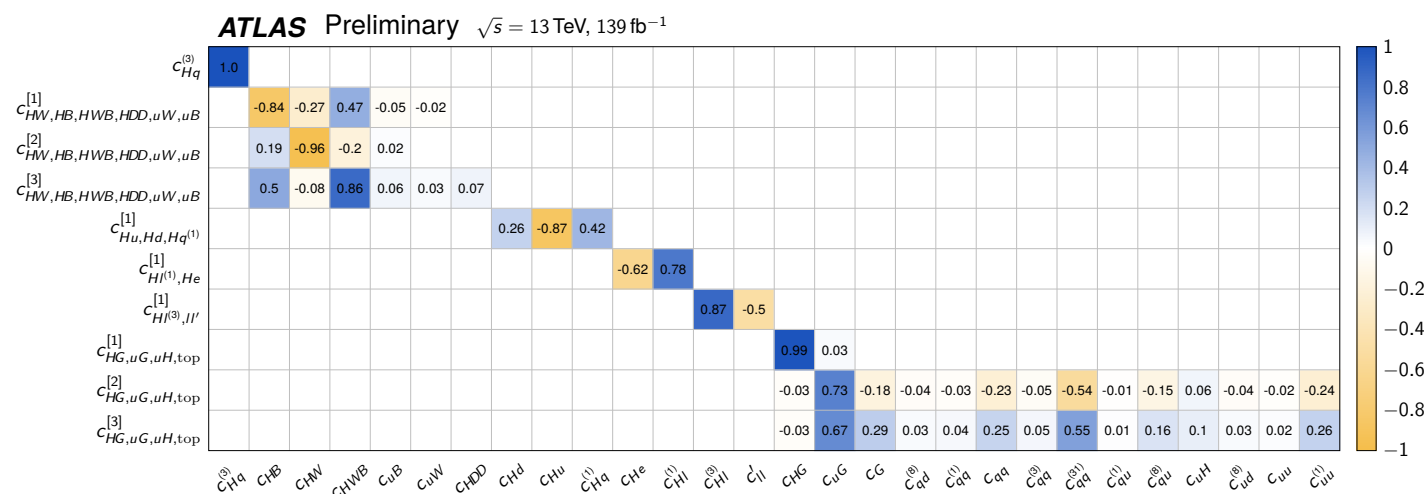
- Look for new physics in the interplay of the off shell and on shell Higgs
 - ▶ Exploit the energy growing sensitivity in polarised vector bosons.
 - ▶ Project measurements of (double) differential cross sections on 4ℓ final state
 - ◆ $qq \rightarrow Z_{(L)} Z_{(L)} + jj$ vs $H \rightarrow gg \rightarrow Z_{(L)} Z_{(L)} (+jj)$
 - ▶ Correlate couplings in different regimes to capture energy dependence.
 - ▶ Interpret measurements in context of EFT.
- Expand measurements to $(H \rightarrow) W_{(L)} W_{(L)} \rightarrow \ell \nu \ell \nu (+jj)$
 - ▶ Tackle $t\bar{t}$ background with MVA methods.
- Investigate sensitivity in lepton colliders through ZH production

Additional material.

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i^{N_{d6}} \frac{c_i}{\Lambda^2} \mathcal{O}_i^{(6)} + \sum_j^{N_{d8}} \frac{b_j}{\Lambda^4} \mathcal{O}_j^{(8)} + \dots$$

- Enhance sensitivity

- ▶ by isolating dependencies in Wilson coefficients (c_i) allowing for simultaneous extraction through eigenvector decomposition of the dependencies.



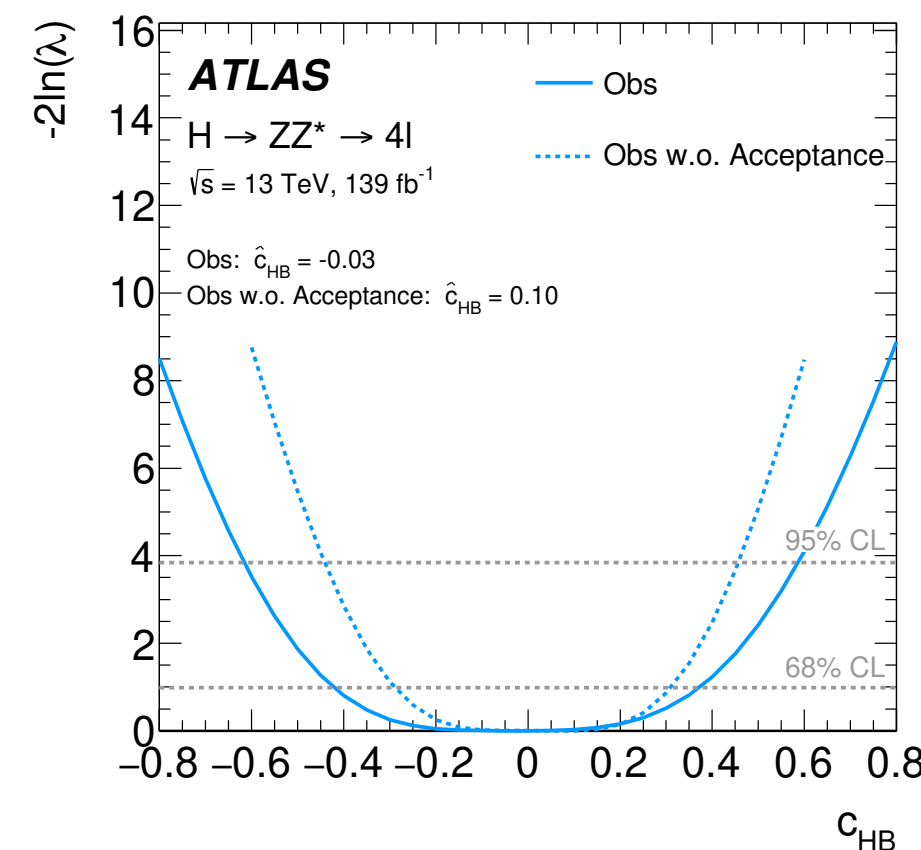
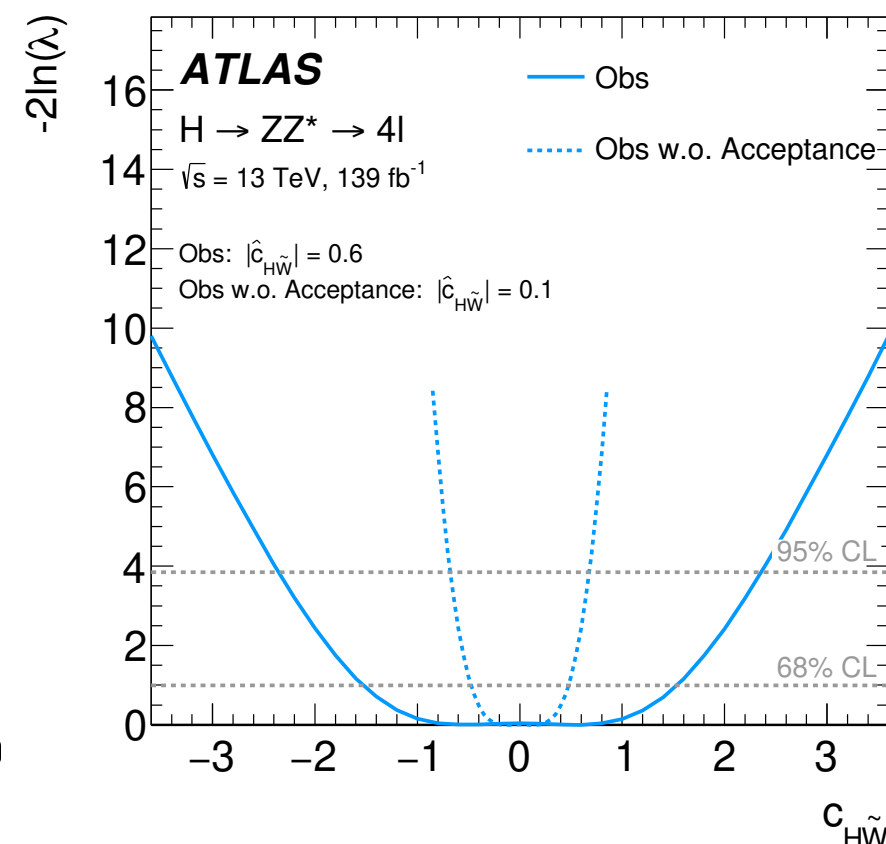
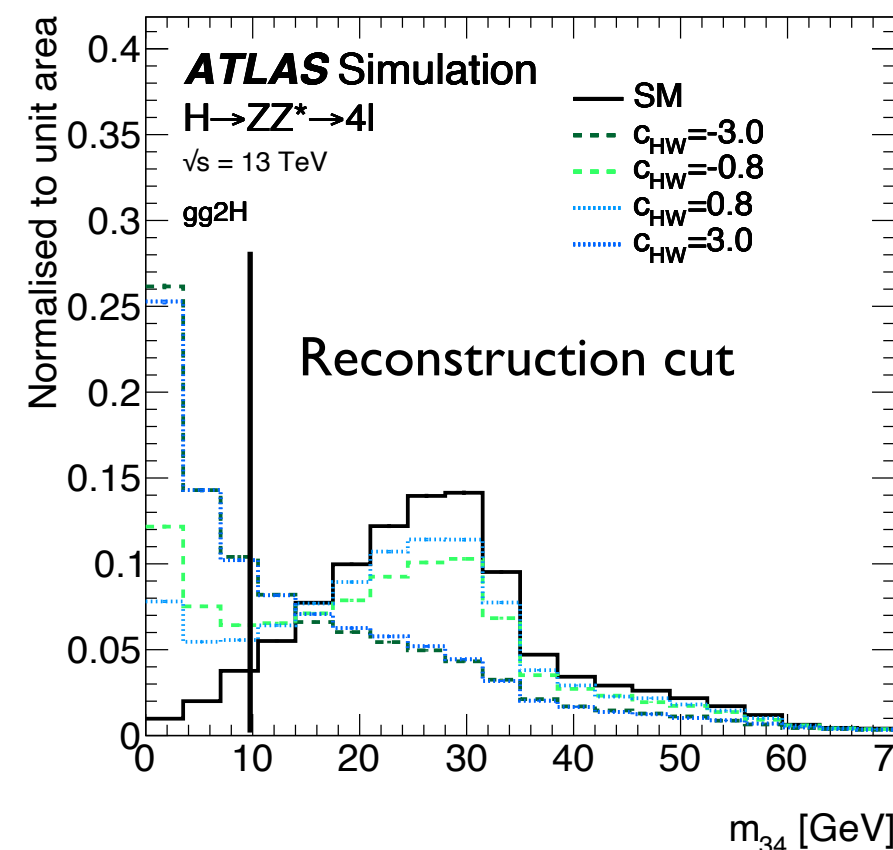
Coefficient	Operator	Example process
c_{HDD}	$(H^\dagger D^\mu H)^* (H^\dagger D_\mu H)$	
c_{HG}	$H^\dagger H G_{\mu\nu}^A G^{A\mu\nu}$	
c_{HB}	$H^\dagger H B_{\mu\nu} B^{\mu\nu}$	
c_{HW}	$H^\dagger H W_{\mu\nu}^I W^{I\mu\nu}$	
c_{HWB}	$H^\dagger \tau^I H W_{\mu\nu}^I B^{\mu\nu}$	
c_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$	
$c_{Hl}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$	
$c_{Hl}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}_\mu^I H)(\bar{l}_p \tau^I \gamma^\mu l_r)$	
c_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$	
$c_{Hq}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$	
$c_{Hq}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}_\mu^I H)(\bar{q}_p \tau^I \gamma^\mu q_r)$	
c_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$	
c_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$	

- Results interpreted in the context of new physics:

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i^{N_{d6}} \frac{c_i}{\Lambda^2} O_i^{(6)} + \sum_j^{N_{d8}} \frac{b_j}{\Lambda^4} O_j^{(8)} + \dots$$

- Standard Model Effective Field Theory as the standard candle.
- Probe for non-SM contributions to the tensor structure of the Higgs boson.

- Account for BSM acceptance effects in kinematic observables of decay products

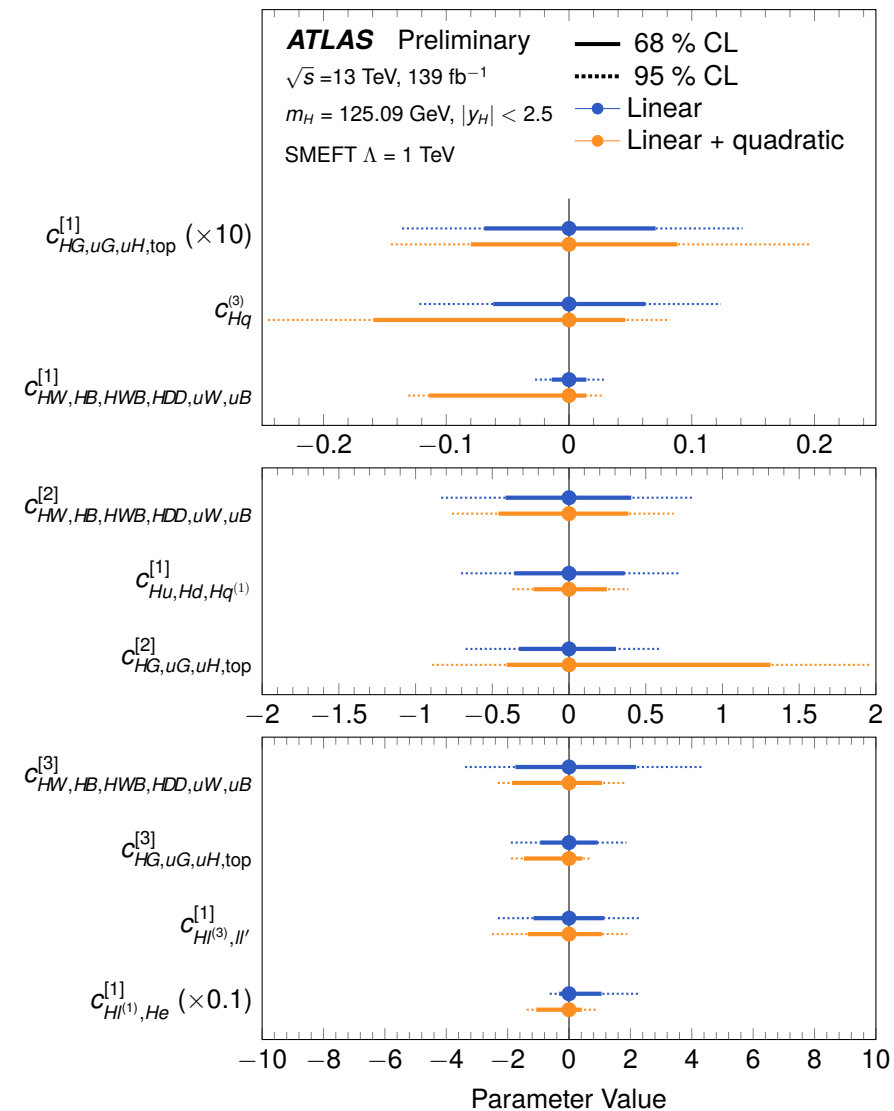
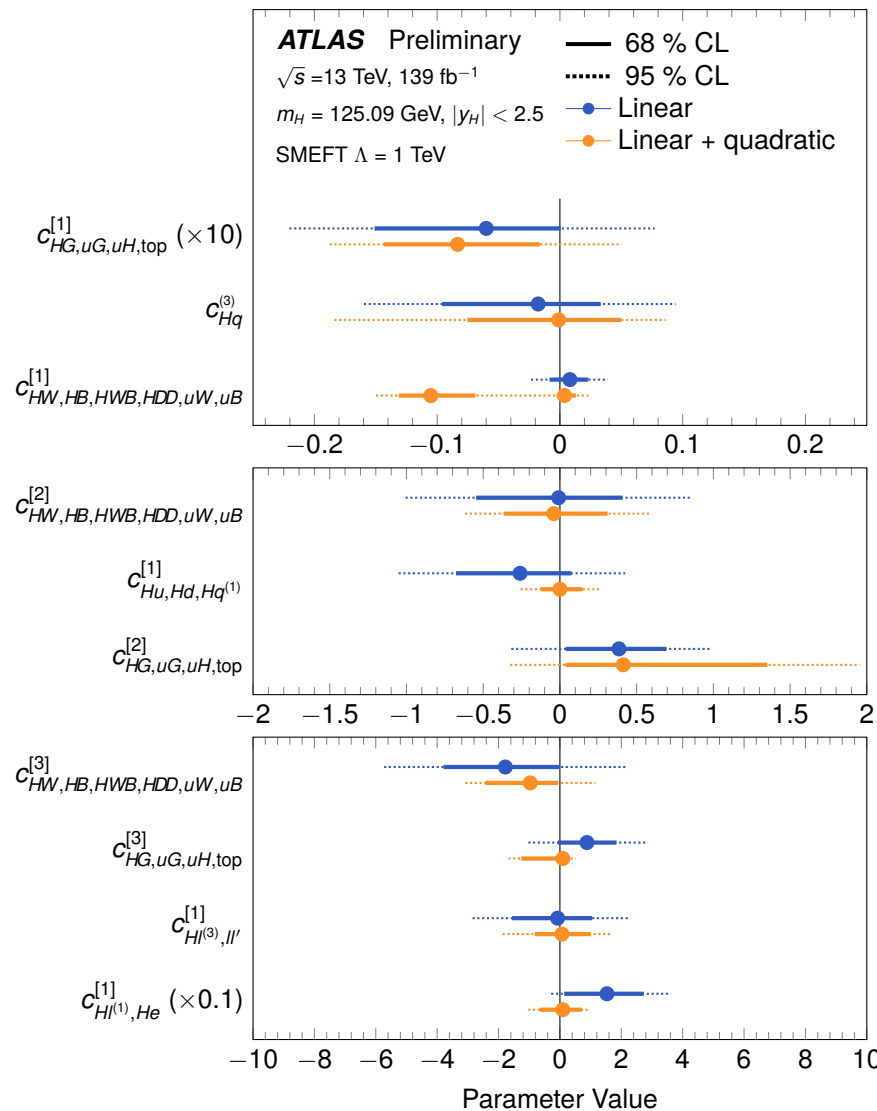


- Results interpreted in the context of new physics:

► Results in both

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i^{(6)} + \sum_j \frac{b_j}{\Lambda^4} \mathcal{O}_j^{(8)} + \dots$$

- ◆ linear approximation for dim-6 operators and,
- ◆ linear plus quadratic approximation for general sensitivity to dim-8, suppressed by Λ^{-4}



Introduction

$$|H|^2 = \frac{1}{2} (v^2 + \boxed{2hv} + h^2 + \boxed{2\phi^+ \phi^- + (\phi^0)^2})$$

- Theorists investigate study of H couplings in off-shell production.

- ▶ Sensitivity in longitudinally polarized vector bosons production.
- ▶ Growth of sensitivity with energy
- ▶ Sensitivity to κ_g κ_V κ_t from:

$$\kappa_t : pp \rightarrow jt + V_L V_L' \quad \kappa_g : pp \rightarrow W_L^+ W_L^-, Z_L Z_L$$

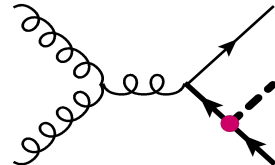
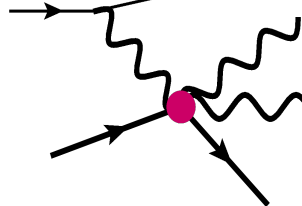
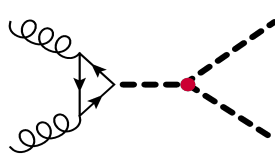
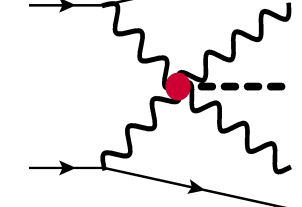
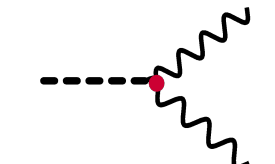
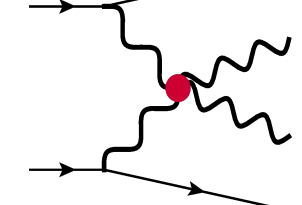
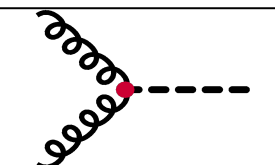
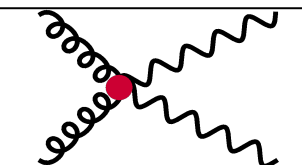
$$\kappa_V : pp \rightarrow jj + V_L V_L',$$

- Sensitivity from on shell production

- ▶ Well-known analyses in the Higgs sector.
- ▶ Sensitivity to κ_g κ_V κ_t from:

- ◆ κ_g differential measurements targeting ggF.
- ◆ κ_V VBF measurements in $ZZ^* WW^*$

- ◆ κ_t (loop) from p_T^H spectra and clean signatures in $t\bar{t}H, H \rightarrow ZZ \rightarrow 4\ell$

		HC	HwH	Growth
κ_t	\mathcal{O}_{yt}			$\sim \frac{E^2}{\Lambda^2}$
κ_λ	\mathcal{O}_6			$\sim \frac{vE}{\Lambda^2}$
$\kappa_{Z\gamma}$ $\kappa_{\gamma\gamma}$ κ_V	\mathcal{O}_{WW} \mathcal{O}_{BB} \mathcal{O}_r			$\sim \frac{E^2}{\Lambda^2}$
κ_g	\mathcal{O}_{gg}			$\sim \frac{E^2}{\Lambda^2}$

- Relation of the two:

- ▶ Identify observables from both classes of processes most sensitive.
 - ✦ Ex: HC: p_T^H, p_T^H vs N_j etc and in HwW: H_T , (angular) distributions sensitive to polarisation.
- ▶ In VBS (HwH) and VBF (onshell) possibility of double simultaneous study from same final state at the two different energy regimes.

- ▶ Plans and stages:

- ▶ MG model for HwW should be available from

$$\begin{aligned} \text{HC: } |\delta\kappa_g| &\lesssim 0.025 \\ \text{HwH: } |\delta\kappa_g| &\lesssim 0.24 / 0.06 / 0.01 \\ \text{HwH (no } \bar{q}q \rightarrow Z_T Z_T) : |\delta\kappa_g| &\lesssim 0.09 / 0.02 / 0.005 \end{aligned} \quad (10)$$

- ▶ Select **longitudinally polarised** vector bosons
- ▶ Onshell production truth samples easily available.
- ▶ Start investigating the sensitivity at truth level and build a rough analysis.
- ▶ If promising, all study backgrounds and detector level quantities.
 - ▶ Delphes or else, still to be discussed.